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Efficiency of the LIFE Laser - Response to a Request for Information from the National Research Council

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EFFICIENCY of the LIFE LASER

Response to a Request for Information from the National Research Council

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System models indicate that the required driver efficiency for inertial fusion energy (IFE) should exceed approximately 12-to-14%, and that further efficiency improvements provide diminishing returns on overall system performance.[1] Notably, these studies show that an optimized system will likely employ drivers with suboptimal efficiency from a purely technical standpoint, due to cost vs. efficiency tradeoffs. For this reason, the LIFE laser point design is optimized for the system (power plant) applications, rather than driver efficiency alone. This document describes the anticipated efficiency of the LIFE laser driver, and the basis for this assessment.

Detailed simulations have been performed to calculate the efficiency of the current LIFE point design as a function of the total diode pump power in the system, which is a significant cost center. Figure 1 shows the results of these simulations, showing how efficiency trades off against diode power (cost). At our selected operating point, the design exhibits efficiency above 18% without cooling. Additional cost/efficiency tradeoffs and design modifications can be performed to vary the baseline design. The additional variability associated with these changes is represented by the gray curves in the figure.

Table I details the impact of various effects on the efficiency of the current LIFE point design at the selected operating point. These effects are grouped into bundles on the right-hand-side of the table. These bundles are associated with (i) conversion of electricity to diode pump light at 872 nm, (ii) delivery and conversion of pump light to stored energy in the solid state gain medium, plus lost energy in the medium due to spontaneous and amplified spontaneous emission (ASE), (iii) efficiency of extracting stored energy at 1053 nm from the gain medium during amplification of a seed pulse, and (iv) conversion of 1053 nm energy to “3 ω ” ultraviolet energy at 351 nm and transport of this energy through the final optical system. The table rolls up efficiencies in the bottom three rows, which show the relevant driver efficiency for IFE (“351 nm electrical-to-optical”) as well as efficiencies that exclude the 3 ω section and or the pump efficiency. Table I also employs a letter code (A,G,M,T) to indicate the primary design factors that influence the efficiency of each process. For example, ASE losses are influenced by the diode pump pulse duration (temporal “T”) and the aspect ratio and size of the gain media (geometry “G”).

Table I compares the LIFE laser point design to “state-of-the-art” values, which likely cannot be achieved for every factor simultaneously in a single design due to conflicting optimization requirements. To assess the impact of such conflicts, one can compare optical-to-optical efficiencies from the pump light to extracted light at 1053 nm. A simple multiplication of Table I “state-of-the-art” values suggests an optical-to-optical efficiency of 66%. Reports for actual diode-pumped solid-state lasers show that integrated systems can operate in the range of 50%.[2] The current LIFE point design has an optical-to-optical efficiency of 39%.

The LIFE laser efficiencies detailed in Table I result from an extensive design process that is grounded in (i) experimental data obtained from the National Ignition Facility[e.g.; 3,4], Mercury laser [5], components for these lasers, and subsystem prototypes for LIFE; (ii) data from component vendors [e.g.; 6-8]; (iii) literature data [e.g.; 9-10]; and (iv) detailed simulations based on design codes that have been validated against experimental laser designs such as NIF and Mercury.[e.g.; 11-12] Details underlying the values reported in Table I are provided in the Appendix.

The efficiency breakout in Table I does not include power for the subsystems required for laser cooling, which employ Helium gas for face-cooling amplifier gain slabs,[5] and a liquid coolant for diode laser pump cooling, removing ASE-generated heat, and cooling miscellaneous other systems (e.g.; beam dumps). The cooling power is assessed using detailed models that include refrigeration thermodynamics (with temperature-, pressure-, and phase-dependent refrigerant and coolant properties), heat exchanger details, and the mechanical work due to pumping coolant fluids. It accounts for power consumed in both coolant and refrigeration subsystems, using standard methods [e.g.; 13-14]. Including the cooling subsystem power, the overall efficiency for this LIFE laser point design is approximately 15%.

In summary, we have employed detailed simulations based on an experience and simulation base proven in previous laser developments to assess the efficiency of the current LIFE laser point design. Our results show that a high energy, pulsed, diode-pumped solid state laser can provide an efficiency of 18% without cooling and 15% with cooling. This laser point design is optimized for overall LIFE plant performance, using a system model that considers system cost and the efficiencies of other plant subsystems. In this context, our driver efficiency results show that the current LIFE laser design meets the requirements for inertial fusion energy (with margin). Laser simulations also show that higher driver efficiencies are achievable using different cost/performance tradeoffs within the system. We anticipate that the laser point design will evolve, resulting in different efficiency/cost optimizations, as the overall LIFE plant design evolves and undergoes further optimization. We also anticipate that additional efficiency improvements will result as the designs for individual laser subsystems undergo further optimization.

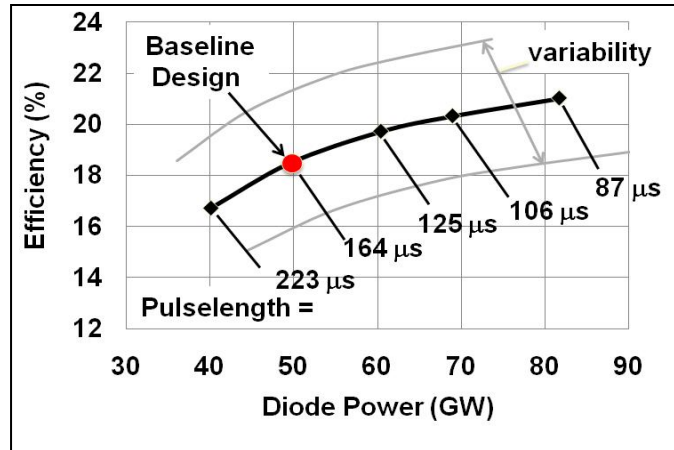


Figure 1: Simulated efficiency of the current LIFE laser point design for a system delivering 2.2 MJ pulses at 351 nm wavelength and 16 Hz repetition rate. The figure shows the tradeoff of driver efficiency (excluding cooling) vs. diode pump power, which is controlled by varying the duration of the pump pulse width. Gray lines show the efficiency variability associated with design tradeoffs. The red dot shows the selected operating point for the current baseline design.

Table I: LIFE Laser Point Design Efficiency Breakout, and Comparison to “State-of-the-Art”

Item with dependence (A = Architecture, G = Geometry, M = Material, T = Temporal)	State of the Art (%)	LIFE (%)	State of the Art	LIFE
DC Power Supply, A	96	95	62%	64%
Electrical Pulsers, A	90	95		
Diodes, M, T	73	72		
Diode Micro-Lenses, G	98	98		
Pump-Light Delivery System, G	99	93	81%	59%
Pump-Light Absorption, G, M	100	99		
Quantum Defect, M	83 (glass)	83		
Spontaneous Emission, Trapping, G, T	99	85		
Amplified Spontaneous Emission, A,G,T	99	90	83%	67%
Saturation Fluence Correction Factor, M	95 (glass)	90		
Extraction Efficiency, A	99	92		
Pump-Light Non-Uniformity, A	99	99		
Mode-Match Factor, A, G	92	92	83%	71%
Infrared transport, A	97	90		
Depolarization , A, M	100	99		
Frequency Conversion, T	84	75		
351 nm transport, A	99	95	<div><div><div></div><div></div></div><div><div>Pulsed solid state lasers have demonstrated similar optical-to-optical efficiency: 50% Feugnet, Opt Lett 20, 157 (1995)</div></div></div>	
351 nm Electrical-to-Optical Efficiency	34*	18		
1053 nm Electrical-to-Optical Efficiency	41*	25		
1053 nm Optical-to-Optical Efficiency	66*	39		

APPENDIX: DESIGN and SIMULATION BASIS for TABLE I

This Appendix provides additional detail regarding the efficiencies reported in Table I, following the sequence laid out in the Table.

1. The AC-DC conversion efficiency value reflects commercial rectification technologies
2. Electrical pulser efficiency reflects a LIFE prototype pulser [15] which currently exhibits 90% efficiency. Circuit simulations show that anticipated improvements in the series resistance of certain components will extend this design to 95% efficiency.
3. Diode efficiency reflects an industry consensus on pumps for LIFE,[6], as well as literature reports for diode lasers operating at 808 and 940~970 nm wavelengths, [e.g.; 16-18] with reported efficiencies >70% from 850 through 980 nm.[19]
4. Pump light delivery and absorption efficiencies are calculated using ray tracing simulations of a LIFE-specific designs for the amplifier cavity and its pump coupling, using measured spectroscopic data for the pump glass.[8-9]
5. The quantum defect is the ratio of pump wavelength to infrared laser emission wavelength.
6. Spontaneous emission is calculated[20] from known excited state lifetimes for the laser glass.[8-9]
7. ASE is calculated using Monte-Carlo techniques that include both geometric and spectral effects.[21] These methods and codes have been validated against experimental data.[e.g.; 4-5]
8. Extraction is calculated using a Frantz-Nodvik approach[20,22] using multiple simulation codes[e.g.; 11-12] that have been extensively validated against high-energy pulse laser systems, and include spatial variations across the beam profile (pump nonuniformity and mode-matching). Input data for the simulations is obtained from measured material cross sections [8-9] and passive optical losses measured for components deployed on NIF [3] or obtained from suppliers. The effects of thermal wavefront distortion and depolarization are simulated using finite element analysis to simulate thermo mechanical fields from simulated pump distribution profiles, using codes that were validated for the design of NIF and Mercury.[23]
9. Harmonic conversion efficiency is calculated using propagation codes [e.g.; 11-12] that account for both spatial and temporal variations in the optical pulse. Results obtained during NIF development show that 84% conversion efficiency can be achieved for short pulses with relatively uniform duration.[3] To facilitate high conversion efficiencies, the LIFE laser point design partitions the laser pulse waveform in a nonuniform fashion across multiple beamlines, all of which illuminate the same spot on the target hohlraum. This concept, illustrated for a 4-beamline case in Figure 2, enables optimization of harmonic conversion efficiency during both the “foot” and “drive” segments of the laser pulse.

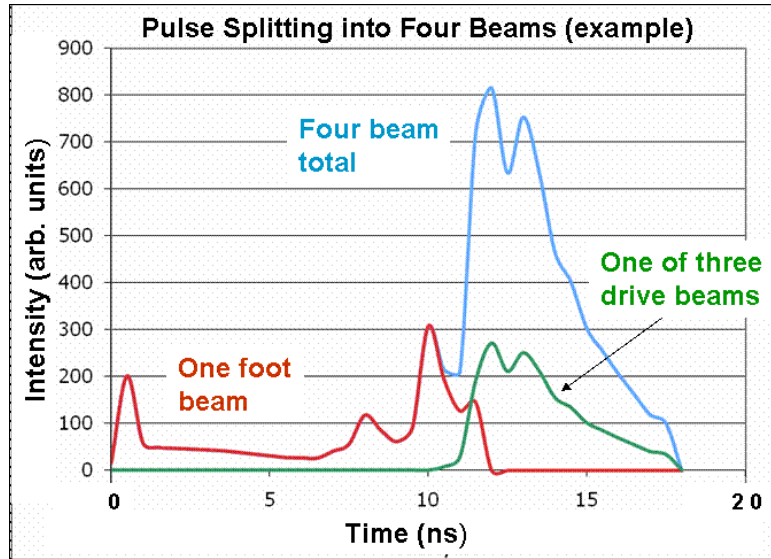


Figure 2: Example pulse splitting approach for harmonic conversion efficiency optimization. The total pulse energy in an illumination spot (blue curve) is partitioned among four beams to maintain more uniform intensity profiles on each converter. In this example, the system employs three beams to generate the “drive” segment of the laser pulse (green curve) and one beam to generate the “foot” portion of the pulse.

REFERENCES

- [1] T. ANKLAM et al., “LIFE: The Case for Early Commercialization of Fusion Energy,” *Digest 19th Topical Mtg. Technol. Fusion Energy*, p. 39 (American Nuclear Society, Las Vegas, 2010).
- [2] G. FEUGNET et al., “High-efficiency TEM₀₀ Nd:YVO₄ laser longitudinally pumped by a high-power array,” *Opt. Lett.* **20**, 157 (1995)
- [3] C. A. HAYNAM et al., “National Ignition Facility laser performance status,” *Appl. Opt.* **46**, 3276 (2007)
- [4] H. T. POWELL et al., “Flashlamp Pumping of Nd:Glass Disk Amplifiers,” *Proc. SPIE* **1277**, 103 (1990)
- [5] A.J. BAYRAMIAN et al., “The Mercury Project: A High Average Power, Gas-Cooled Laser for Inertial Fusion Energy Development,” *Fusion Sci. & Tech.*, **52**, 383-387 (2007)
- [6] R.J. DERI et al., “Semiconductor Laser Diode Pumps for Inertial Fusion Energy Lasers”, UCRL-TR-465931 (Lawrence Livermore National Laboratory, 2011)
- [7] S. KRENITSKY/SCHOTT ADVANCED OPTICS, “Manufacture of APG-1 Laser Glass Slabs for the LIFE Laser Program” (2011)
- [8] SCHOTT AG ADVANCED OPTICS, “APG-1 Phosphate Laser Glass,” www.schott.com/advanced_optics.

- [9] S.A. PAYNE et al., “Laser properties of a new average-power Nd-doped phosphate glass,” *Appl. Phys. B*, **61**, 257 (1995)
- [10] C.A. Ebberts et al., “Optical absorption at 1.06 μm in highly deuterated potassium dihydrogen phosphate”, *Appl. Opt.* **31**, 1960 (1992)
- [11] R. A. SACKS et al., “The PROP92 Fourier beam propagation code,” *ICF Annual Report*, UCRL-LR-105821-96, pp. 207-213 (Lawrence Livermore National Laboratory, 1996)
- [12] O. MORICE, “Miro: Complete modeling and software for pulse amplification and propagation in high-power laser systems,” *Opt. Eng.* **42**, 1530 (2003)
- [13] W.M. KAYS and A.L. LONDON, Compact Heat Exchangers (3rd Edition; Krieger Publishing, 1998).
- [14] K.A. Manske et al., “Evaporative condenser control in industrial refrigeration systems,” *Int. J. Refrigeration* **24**, 676 (2001)
- [15] A. J. BAYRAMIAN et al., “Compact, efficient, low-cost diode power conditioning for laser inertial fusion energy”, to appear in *Proc. SPIE* **7916** (2011).
Photonics West paper 7916-10.
- [16] P. CRUMP et al., “Passively Cooled TM Polarized 808-nm Laser Bars with 70% Power Conversion Efficiency...,” *Photon. Technol. Lett.* **20**, 1378 (2008)
- [17] P. CRUMP et al., “Diode Laser Bars Deliver > 400-W Peak CW Power from 800-nm to 980-nm...,” *Proc. SPIE* **6397**, 639706 (2006)
- [18] M. KANSKAR et al., “73% CW power conversion efficiency at 50W from 970nm diode laser bars,” *Electron. Lett.* **41**, 245 (2005)
- [19] P. CRUMP et al., “Diode Laser Efficiency Increases Enable > 400-W Peak Power from 1-cm Bars...,” *Proc. SPIE* **6104**, 610409 (2006)
- [20] W. KOECHNER, Solid-State Laser Engineering (5th Edition; Springer, New York; 1999)
- [21] G. LE TOUZE et al., “3D Gain Modeling of LMJ and NIF Amplifiers,” *Proc. SPIE* **3492**, 630 (1999)
- [22] L.M. FRANTZ et al., “Theory of Pulse Propagation in a Laser Amplifier,” *J. Appl. Phys.* **34**, 2346 (1963)
- [23] A.L. BULLINGTON et al., “Thermal birefringence and depolarization compensation in glass-based, high average power laser systems”, to appear in *Proc. SPIE* **7916** (2011). Photonics West paper 7916-30.